Properties of the Outer Halos of Galaxies from the Study of Globular Clusters

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This paper reviews some recent work on the properties of the outer halos of galaxies. I particularly focus on recent and upcoming advances made with the study of globular clusters. Globular clusters can be observed out to $\sim$ 100 kpc from the centers of galaxies, allowing the study of galactic halos well beyond the regions probed by many other techniques such as observations of the integrated light of galaxies. In the few well-studied cases to date, the study of globular cluster systems has provided dynamical evidence for dark matter halos around elliptical galaxies, and demonstrated kinematic differences between different globular cluster populations that shed light on the formation history of their host galaxies.

1 Why Outer Halos?

One of the primary motivations for studying the outer halos of galaxies is to study the nature of dark matter. The reason the outer halos of galaxies are important for addressing the nature of dark matter is that most galaxies are only dark matter dominated at large distances from their centers. In the inner regions of galaxies ($r \lesssim R_e$), the observed stars and gas typically make a significant contribution to the mass budget. Exactly what that contribution is for different galaxies remains a subject of active research and vigorous debate. This vigorous debate is symptomatic of the problem of determining the dark matter content of the inner parts of galaxies accurately. Specifically, because the observed baryons make up a non-negligible fraction of the mass in the inner regions of most galaxies, an accurate determination of the dark matter properties in these regions requires a very accurate accounting of the mass contribution of these baryons. Since it is a severe challenge to achieve such an accurate accounting of the baryonic mass in the inner regions of galaxies, the dark matter properties of the inner regions of galaxies remain somewhat uncertain. Moreover, in regions in which baryons are a significant fraction of the mass, the dissipation, star formation, and feedback that can happen in the baryons may affect the distribution of the dark matter. Although it is possible to study special classes of objects (e.g. low surface brightness galaxies) for which the observed baryons appear to be negligible in the mass budget at all radii, this approach still leaves open the question of the dark matter properties of galaxies in general. An obvious path to take is to study the outer halos of galaxies in which the baryonic contribution is much smaller, and one can obtain a “clearer” view of the dark matter around galaxies.

A second motivation for studying the outer halos of galaxies is that the outskirts of galaxies have long dynamical times, and therefore these regions may retain more of a memory of their initial conditions than central regions for which the crossing times are much smaller than the Hubble time. Specifically referring to the shapes of galaxies and their halos, it is possible that the outer regions might more closely reflect the initial conditions, while various dissipative processes may re-arrange the matter in the central regions.

A third reason for studying the outer halos of galaxies is that they are still uncharted territory. Why this is the case, and some possibilities for making advances in this area are the subject of the following sections.

2 Why Globular Clusters?

The most significant challenge to studying galaxies at large distances from their centers is that there is very little light in the regions to observe. For galaxies rich in neutral hydrogen, HI disks can be traced to large radii, and these provide valuable constraints on the dark matter profile at large radii. These constraints on the dark matter profiles provided by extended HI rotation curves are some of the strongest available. However, even in these cases, one would ideally like to constrain the shape of the dark matter halo in a galaxy and not just its profile. This has proven to be a very challenging task (see review by Sackett 1999).

Early-type galaxies do not have an easily observed tracer such as HI, so one needs to look for other ways to constrain the mass profile of these galaxies. One approach is to determine the velocity dispersion of the integrated light. However, as shown in Figure 1, the integrated light of these galaxies drops rather rapidly with increasing radius, and falls well below the sky brightness at very modest radii. As a result, even the most dedicated attempts with large telescopes have not been able to constrain the velocity dispersion of the stars beyond about $2R_e$, and radial limits of about half of that are more typical. Data adequate to characterize the higher order moments useful for constraining the orbital anisotropy are at least as limited in radial extent. Moreover, one would also like to study the stellar populations of galaxies at large radii, and the rapid decline of the surface brightness of the integrated light of all galaxies makes this a daunting challenge.

Globular clusters provide a valuable tracer of both the kinematics and the stellar populations of galaxies out to large radii. Firstly, as individual dense collections of stars, there is no problem observing globulars that are present at large radii. Secondly, as shown in Figure 1, globular clusters have

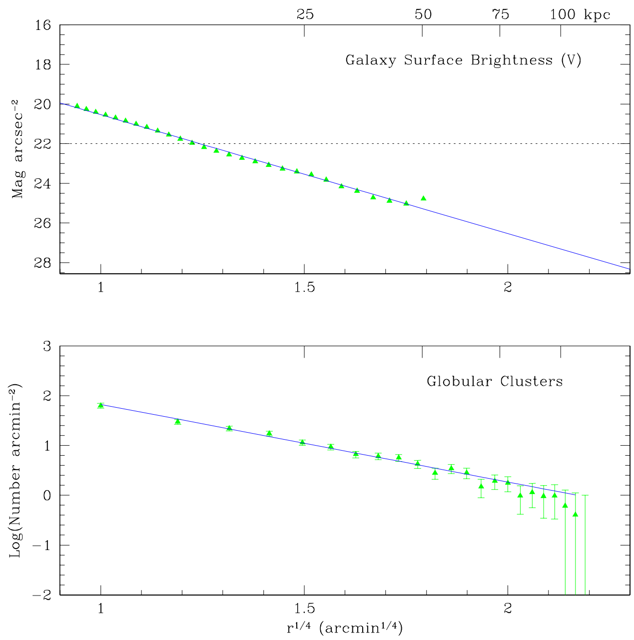

Figure 1: A plot of the surface density against radius of the starlight (upper panel) and globular clusters (lower panel) for the Virgo elliptical NGC 4472 (data from Rhode & Zepf 2001). The light dashed line represents the surface brightness of a dark sky. This plot demonstrates the great difficulty extending studies of the integrated light to large radii. The greater spatial extent of the globular cluster system relative to the integrated light is also clearly seen.

extended spatial distributions, so they can be found in useful numbers at large radii, particularly around luminous ellipticals which typically have populous globular cluster systems. Thirdly, globular cluster systems provide information both about the dynamics of the outer halos of galaxies through their radial velocities, and about the chemical enrichment and possibly even age through their photometric and spectroscopic properties.

Planetary nebulae are also valuable probes of the outer halos of galaxies. Like globular clusters, each planetary nebulae can be observed equally well no matter how far away it is from the center of its host galaxy. They also have the advantage that much of their light is emitted in a single line, so obtaining an accurate radial velocity for a planetary nebula can be straightforward. However, the surface density of planetary nebulae does not have the large spatial extent of the globular cluster systems, and they have not yet provided as much information about the formation history of galaxies at large radii as globulars. A final approach, reviewed at this meeting by David Buote, is to use the properties of the hot gas emitting in X-rays found around luminous early-type galaxies. With sufficiently accurate X-ray imaging spectroscopy, it is feasible to determine the dark matter distribution and metal abundances in hot gas, as well as testing for asymmetries that might indicate objects for which the assumption of hydrostatic equilibrium in the gas at large radii is questionable. An obvious goal is to combine as many approaches as possible, as they each have different sets of assumptions and possible systematic errors, which might be revealed through careful intercomparison.

3 Two Dimensional Shapes and Inferences about Three-Dimensional Distributions

The two dimensional distribution of light in galaxies has been fairly well characterized within about $1R_e$. One of the uses of these data is to try to constrain the three-dimensional shapes of galaxies. An unconstrained inversion of two-dimensional data to the intrinsic three-dimensional shape is problematic (Rybicki 1987), but either through constrained inversion techniques (e.g. Ryden 1992, Lambas, Maddox, & Loveday 1992) or through the addition of kinematic data (e.g. Franx, Illingworth, & de Zeeuw 1991, Bak & Statler 2000), some progress can be made. Overall, the evidence suggests that at least a small amount of triaxiality is common, with most galaxies being nearly oblate and a modest fraction nearly prolate.

It would be of clear interest to extend these studies to the outer regions of galaxies which might be less influenced by evolution and more closely reflect the conditions when they formed. CCD Mosaics covering larger areas are beginning to make this feasible, although the large surveys of galaxies used in the statistical studies given above are a long way away. Both the integrated light and the globular clusters can be studied this way, with the integrated light offering much more signal, and the clusters potentially reaching to larger radii, but being limited by defining the two-dimensional shape with a modest number of points.

As an example of how this work might develop in the future, we present in Figure 2 our new results for the position angle and ellipticity of the integrated light and globular clusters around NGC 4472. The position angle of the globular cluster system is consistent with that of the integrated light over the same radial range. The latter qualification matters, since our data confirm that there is a position angle twist in this galaxy, which can be taken as evidence for some level of triaxiality. The ellipticity of the globular cluster system is marginally smaller (rounder) than that of the galaxy light, but this requires confirmation by additional data.

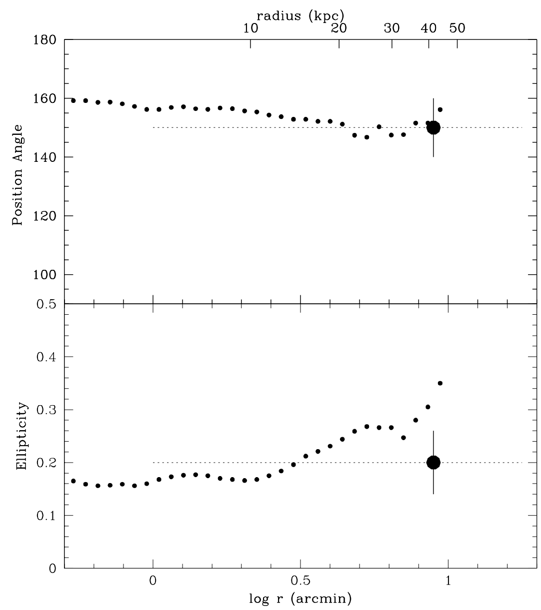

Figure 2: The position and ellipticity as a function of radius for the starlight (plotted as small dots) and the globular clusters (plotted as a large dot) in NGC 4472. The globular cluster point is a radial average over the range indicated by the light dashed line, with the radial location of the dot as the approximate median radius of the globular cluster sample. The uncertainty in the position angle and ellipticity of the NGC 4472 globular clusters system is given by the vertical line about the globular cluster point. This analysis is based on the Mosaic images presented in Rhode & Zepf (2001). This plot shows that the position angle of the globular cluster system is consistent with that of the integrated light over the same radial range. The ellipticity shows marginal evidence that the globular cluster system is slightly rounder than the galaxy, but this requires confirmation by additional data.

4 Radial Velocities

4.1 Kinematics of Individual Populations

One of the valuable applications of radial velocities of substantial numbers of globular clusters around elliptical galaxies is to compare the kinematics of the metal-rich and metal-poor globular clusters previously identified in photometric studies. The kinematics of these systems can shed light on their formation

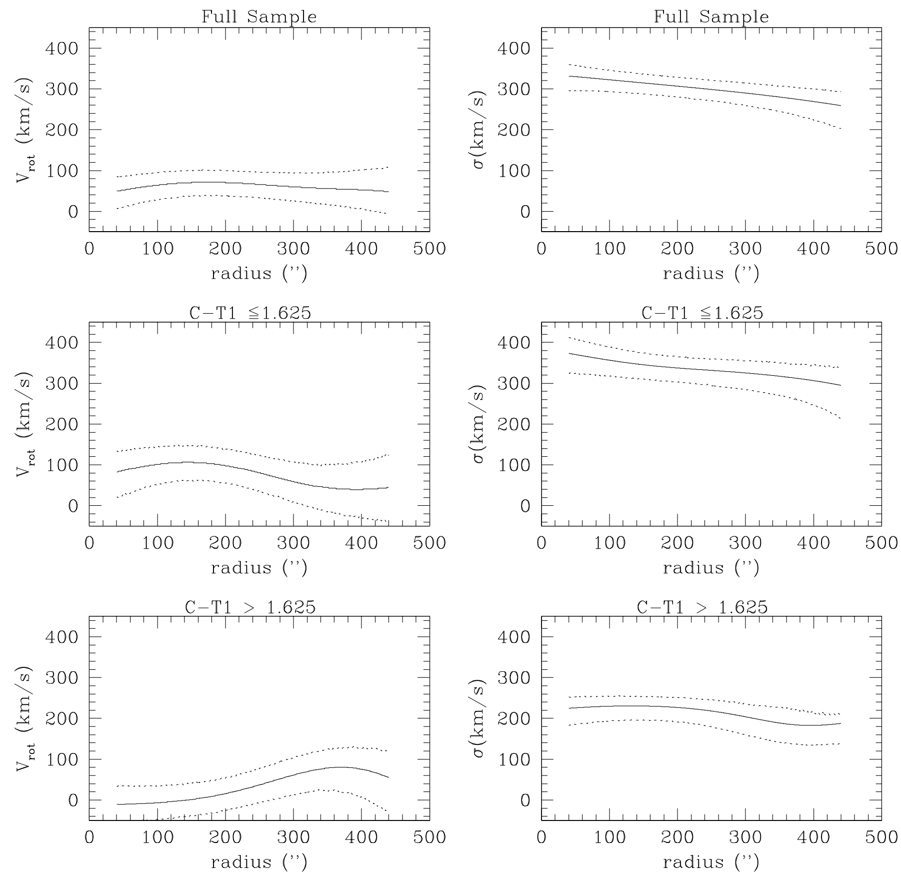

Figure 3: Plots of the rotation and velocity dispersion fields for the globular clusters of NGC 4472 from Zepf et al. (2000). The top panels are for the full data set, the middle panels for the metal-poor (blue) clusters and the bottom panels for the metal-rich (red) clusters. A Gaussian kernel with $\sigma = 100''$ was used for the radial smoothing for all of the datasets. The dotted lines show the 1σ uncertainties, as determined from bootstrapping. The curves are highly correlated in the radial direction with the smoothing used. The plots show modest rotation in the full sample and the metal-poor cluster population which is essentially constant with radius. The red sample has essentially zero rotation at small radius and a tentative (1σ) rise to modest rotation at larger radii. The velocity dispersion is significantly larger than the rotation at all radii.

history. As an example, results from our recent study of the NGC 4472 cluster system are shown in Figure 3. These data confirm our earlier result (Sharples et al. 1998) that the metal-poor globulars have a larger velocity dispersion than the metal-rich globulars. Perhaps most importantly, the results shown in Figure 3 indicate that the metal-rich globular cluster system has little or no rotation, with an upper limit of $(v/\sigma)_{proj} < 0.34$ (99% confidence level). The absence of rotation in the metal-rich population in this elliptical strongly distinguishes NGC 4472 from spirals like those in the Local Group, which have metal-rich cluster populations with significant rotation. This result argues against models in which all metal-rich systems formed more or less similarly with the only difference being the mass of the central forming "bulge". Instead, the comparison of the significant rotation in the metal-rich Galactic clusters with the insignificance of rotation in the metal-rich clusters of NGC 4472 suggests a model in which elliptical galaxies like NGC 4472 form in major mergers which create the metal-rich globular cluster population and transfer angular momentum outwards, while disk galaxies like the Milky Way have only had more minor mergers, which may lead to modest amounts of globular cluster formation but which are not as efficient at angular momentum transfer.

It is of interest to compare the results for NGC 4472 to those of other ellipticals. There are two other galaxies for which published data are sufficient to make reliable statements about the kinematics of their globular cluster systems. One of these is M87, the central galaxy in the Virgo cluster. Here Côté et al. (2001) used data from Cohen (2000), Cohen & Ryzhov (1987) and their own observations to find $(v/\sigma)_{proj} \sim 0.4$, although with large error bars because of large uncertainties in the rotation. There is evidence that much of the rotation signal comes from the outer regions (see also Kissler-Patig & Gebhardt 1998), so modest rotation and significant angular momentum transport is also suggested for the metal-rich system of this giant elliptical. The third system with significant data is the recent merger, NGC 5128 (Cen A). The kinematics here appear to be different, in that the metal-rich system appears to be rotating significantly, while the metal-poor system shows little rotation (Hui et al. 1995 and references therein). Possible differences between this system and that of NGC 4472 and M87 are that the NGC 5128 system has not yet come to equilibrium and transported angular momentum outwards, or that NGC 5128 is a lower luminosity elliptical which tend to be more rotationally supported.

4.2 Mass Profiles

Measurements of the radial velocities of globular clusters also provide information about the mass distribution of the host galaxy and the orbits of the

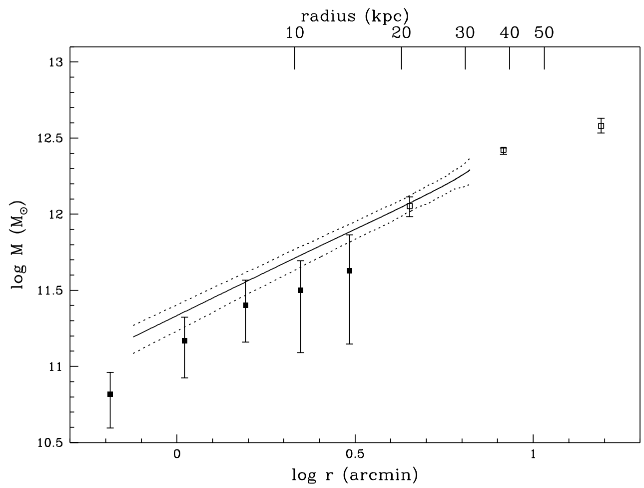

Figure 4: A plot of the mass of NGC 4472 as a function of radius from Zepf et al. (2000). The lines are masses inferred from the radial velocities of the globular clusters. The central solid line is the best fit to the 144 radial velocities discussed in this paper. The dotted lines are the 1σ lower and upper limits determined via bootstrapping. All of these are based on the assumption of isotropic orbits for the globular clusters. The points are masses inferred from ROSAT observations of the hot gas around NGC 4472 (Irwin & Sarazin 1996). The open squares represent points for which the assumption of hydrostatic equilibrium on which the X-ray masses are based may be uncertain because the X-ray isophotes are irregular at these radii. The overall agreement between the masses inferred from the two techniques is good, suggesting that the assumptions underlying each approach are probably roughly correct. The conclusion that then follows is that NGC 4472 has a substantial dark halo, with a mass-to-light ratio at several tens of kpc that is at least a factor of five greater than in the inner regions of the galaxy.

clusters. Globular clusters are particularly useful probes of the dynamics of the outer halos of elliptical galaxies because they can be observed out to much larger radii than it is possible to obtain spectroscopy of the integrated light. A very large number of velocities are required to independently determine the mass distribution and the orbits of the tracer particles in a completely non-parametric way (e.g. Merritt & Tremblay 1994). However, if the mass distribution inferred from X-ray observations and the assumption of hydrostatic equilibrium in the hot gas is adopted, the orbits of the globular clusters can be constrained. Conversely, if assumptions are made about the cluster orbits (e.g. that they are isotropic), then the mass distribution can be estimated. In practice, a sensible approach is to check for consistency of the mass distribution determined via the X-ray observations of the hot gas with dynamical measurements (possibly both from globulars and planetary nebulae) given simplifying assumptions about the orbits, as each technique has its own systematic concerns which are mitigated if the independent approaches agree.

In Figure 4, we present the mass profile of NGC 4472, estimated from the velocity dispersion profile given in Figure 3 and the density profile of the clusters given in Figure 1. We also show for comparison the mass profile estimate based on X-ray observations of the hot gas around this galaxy. The general agreement in these two mass estimates suggests both techniques are probably not beset by terrible systematic errors, and thus provides further evidence for the existence of massive dark halos around elliptical galaxies. The agreement between the two independent mass estimates also suggests that the assumption of isotropic orbits used to obtain the mass estimate from the globular cluster velocities is unlikely to be dramatically off. Similar results are found for M87 (e.g. Côté et al. 2001, Romanowsky & Kochanek 2001, Cohen & Ryzhov 1997). In detail, anisotropy is required at some level for the NGC 4472 globular cluster system because the flattening of system can not be supported by the negligible rotation observed. This is not necessarily true of the M87 system. One of the potential advantages of the study of individual tracers (either globular clusters or planetary nebulae) is that both shape and kinematic information covering the full two-dimensional projected distribution on the sky are obtained (unlike single slices from standard long-slit spectroscopy), which may be useful for future larger studies that attempt to constrain the three-dimensional shape of galactic halos.

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